A large, high performance, curved 2D position-sensitive neutron detector ☆

J. Fried, J.A. Harder, G.J. Mahler, D.S. Makowiecki, J.A. Mead, V. Radeka, N.A. Schaknowski, G.C. Smith, B. Yu*

Brookhaven National Laboratory, Instrumentation Division, Building 535B, Upton, NY 11973, USA

Abstract

A new position-sensitive neutron detector has been designed and constructed for a protein crystallography station at LANL's pulsed neutron source. This station will be one of the most advanced instruments at a major neutron user facility for protein crystallography, fiber and membrane diffraction. The detector, based on neutron absorption in ^{3}He, has a large sensitive area of 3000 cm^2, angular coverage of 120°, timing resolution of 1 μs, rate capability in excess of 10^6 s^{-1}, position resolution of about 1.5 mm FWHM, and efficiency > 50% for neutrons of interest in the range 1–10 Å. Features that are key to these remarkable specifications are the utilization of eight independently operating segments within a single gas volume, fabrication of the detector vessel and internal segments with a radius of curvature of about 70 cm, optimized position readout based on charge division and signal shaping with gated baseline restoration, and engineering design with high-strength aluminum alloy. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

A new, large area spectrometer, based on the gas proportional detector, is in its final stage of construction for an advanced neutron-based, protein crystallography beam-line at the LANSCE spallation source of Los Alamos National Laboratory. A major purpose of this project has been to develop a detector that not only has the best characteristics from previous devices built by our group, but also incorporates new features that will permit the crystallography station to take full advantage of the relatively high flux, wide angular coverage and time structure available from the beam line. Some key specifications are a count rate capability in excess of one million per second, a sensitive area of 0.3 m^2, a timing resolution of about one microsecond, and a position resolution of about 1.5 mm FWHM.

The new detector is built upon the expertise gained by our group over a number of years in building position-sensitive neutron detectors for both small and large angle scattering studies at reactor experiments [1,2]. These are based on
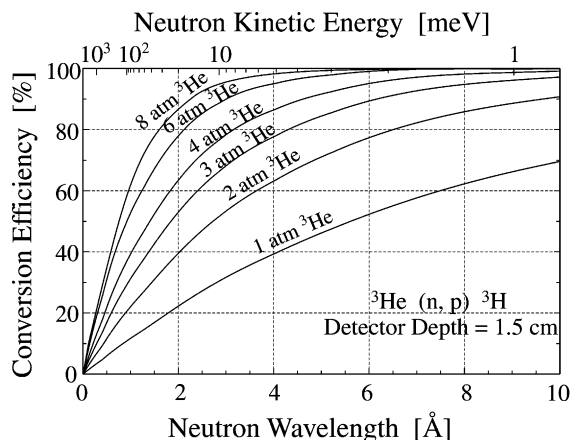
Fig. 1. Neutron absorption efficiency as a function of neutron wavelength in 1.5 cm of ^{3}He.

neutron absorption in ^{3}He followed by low gain multiplication in a 2D wire proportional chamber. Induced charge on two crossed-wire cathodes is used to determine each event's x, y position: a cathode charge interpolation technique permits a position accuracy that is much greater than the readout spacing, though in practice the resolution is determined by the physical range of the neutron reaction products. The two cathodes are constructed with resistive charge division, with multiple readout nodes along the RC line that improve absolute position accuracy/stability and reduce electronic noise compared with simpler, two-channel charge division [3]. A typical device consists of planes of electrodes constituting the cathode–anode–cathode array, a total gas depth of about 15 mm, an active area of 20 cm × 20 cm, contained in an aluminum pressure vessel. The efficiency of ^{3}He over a range of pressures is shown in Fig. 1. Taking account of the approximately 90% transmission of the aluminum entrance window, 6 or 7 atm ^{3}He yields absolute efficiencies in excess of 50% for wavelengths above 1 Å.

2. Detector description

The experimenter's specification that angular coverage be 120° required the detector to be designed in the form of an arc. The desired angular resolution of about 0.1° is attained with a radius of curvature of approximately 70 cm. Thus, it was determined fairly simply that eight independent segments of wire chambers, each reflecting the size of our earlier planar devices [2], would satisfy the angular coverage and also provide increased count rate through parallelism of their readout. Several other important features are incorporated into the design:

(1) The wire frames themselves should conform to the appropriate radius of curvature of the detector in order to maintain a linear position readout and uniform detection efficiency.
(2) The segments are designed to be modular, and are neutron sensitive all the way to their edges. An engineering design has been developed, which permits segments to be abutted with no gap, in a common gas volume. Together with a special readout technique, the boundary regions of the segments are continuously sensitive.
(3) Within each segment, the anode and cathode wires are constructed with an arrangement that significantly reduces anode wire position modulation across the anode wires [4].

The detector operates at a pressure of approximately 2.5 atm of propane and 7 atm of ^{3}He, with a circulating gas purification system.

The charge signal from each cathode node is processed by charge sensing preamps, followed by newly developed gated baseline restorer (GBLR) circuits [5]. The GBLR outputs are digitized by ADCs and the ionization centroid is calculated using an optimized algorithm with a DSP (Digital Signal Processor) and FPGA (Field Programmable Gate Array) dedicated to each segment. The centroid position for each neutron events is sent to a data acquisition system developed by a team at LANL [6].

3. Some key accomplishments

3.1. Pressure vessel

The major components of the pressure vessel are a stainless-steel flange, onto which each of the
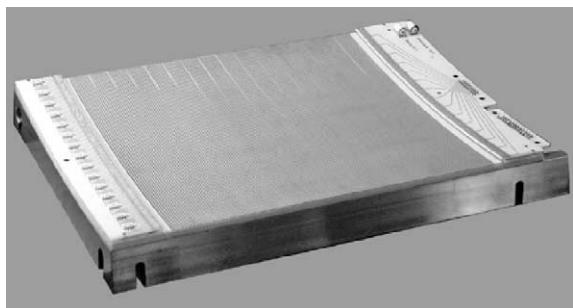
Fig. 2. Photo of a complete wire segment.

Fig. 3. The complete 120° detector.

eight segments is bolted, and an aluminum vessel that seals against the flange with a double O-ring gasket. The vessel is fabricated by Allied Engineering Inc.[1] from a single piece of high-strength aluminum 7075 alloy with a window thickness of 8 mm. The designed maximum operating pressure is 155 psig with a safety factor of 4 required by safety regulations.

3.2. Wire segments

These are built on a solid base of aluminum, machined to an exact radius of curvature. Printed circuit board and wire frames are epoxy bonded to the base with a purpose-designed press that maintains the correct radius of curvature. Fig. 2 shows a completed single segment—this has an angular coverage of 15°. Gold plated tungsten wires and copper strips with spacings of 1.6 mm make up each segment. The completely assembled detector is shown in Fig. 3.

3.3. Readout electronics

The front-end electronics is designed to read out the detector signals and to feed them to ADCs for position analysis. Each node of the cathodes feeds:

(1) A preamplifier, which integrates the detector current signal.
(2) A buffer circuit, which provides a gain of about 16 and a differential output to drive a twisted-pair cable.

(3) A shaping circuit composed primarily of a Gated Base Line Restorer (GBLR) to provide pole-zero cancellation, tail cancellation and base line restoration. It is a time variant, double differentiation equivalent filter, a sample & hold circuit (analog memory stage) to maintain the measured value until the digitization.

The eight sets of front end electronics can be seen in Fig. 3.

3.4. Decoding electronics

This comprises FPGAs and DSPs which accept the digitized x and y signals and build up a two-dimensional histogram in real time, which is viewable on a liquid crystal display. Fig. 4 shows a digital centroid finding circuit (VME 9U card) for one detector segment. An overlapping readout scheme ensures that events at the boundaries of the segments are correctly processed, effectively forming a single seamless detector, 150 cm × 20 cm in area.

4. Initial experimental results

At present, our primary source of neutrons is a low flux Am/Be source. This is sufficient for uniform irradiation testing, but not powerful enough to generate collimated beams for resolution testing. Position resolution measurements have therefore been carried out on a single segment with collimated X-rays, as a function of anode charge level. By this method, we can establish the noise level of the system at the anode charge level the detector is designed to work with
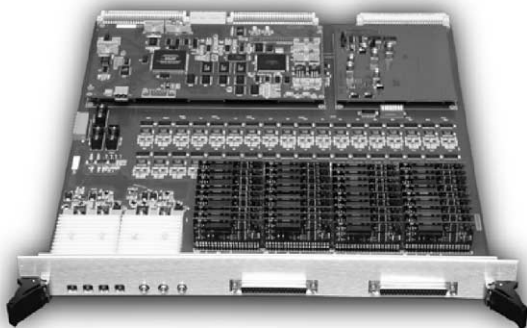
Fig. 4. The digital centroid finding circuit board for one detector segment.

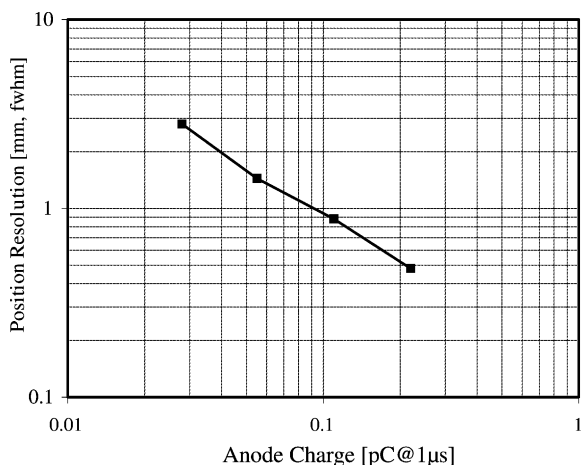Fig. 6. An X-ray transmission image of a 17 cm long copper/kapton mask.

Fig. 5. Position resolution as a function of anode charge along the Y-axis of the detector. The measurements were done using a collimated beam of 5.4 keV, X-rays and a gas mixture of Ar/CO_2 (20%).

for neutrons, which is 0.1 pC. This charge level can be achieved from neutrons with a modest gain of about 50, a value that contributes to long operating lifetime of these types of detector [2].

4.1. Position resolution

A special housing was fabricated from Lucite and mylar to permit low energy X-rays to be used. Fig. 5 shows the results. It is important to bear in mind that the ultimate resolution limit for this

energy of photon is about 100 μm; thus, the curve illustrates the electronic noise limit to resolution. At 0.1 pC anode charge, this limit is just below 1 mm FWHM, consistent with a measured noise charge of 4800 e rms from the amplifier chain [5].

For neutrons, the gas limit to resolution is determined primarily by the propane pressure—it is about 1.3 mm for our choice of 2.5 atm. The expected neutron resolution is the quadratic addition of the noise and the gas limit, or about 1.5 mm FWHM.

4.2. Linearity

A qualitative measure of the uniformity of response and good position linearity is shown in Fig. 6. This is an X-ray transmission image of the new BNL logo that was produced on copper-clad kapton by normal printed circuit etching. The mask has the copper etched away in the locations of the letters. The maximum extent of the letters horizontally is about 17 cm, nearly the complete width of one segment. The image shows slight modulation horizontally due to the anode wires (actually the Y-axis), but the value is less than 10% peak to peak, significantly reduced compared with normal construction methods of high resolution wire detectors [4].

4.3. Boundary response

The outermost anode wire on each side of a segment is electrically isolated from the rest. When two segments are abutted, the two adjacent edge wires are coupled together and biased from a separate supply. This permits fine tuning of the

Table 1
Detector key parameters

Active area	1.5 m × 20 cm (8 segments)
Angular coverage	120° (curved) in X, 15° in Y
Position encoding method	MWPC, resistive charge division on cathode strips/wires
Position decoding method	FPGA+DSP, center of gravity calculation
Event processing time	∼4 μs per segment
Gas mixture	7 atm ^{3}He + 2.5 atm propane
Gas depth	1.5 cm
Nominal gas gain	50
Wire pitch	1.6 mm
Position resolution	1.5 mm FWHM for thermal neutrons
Detection efficiency	∼50% @1 Å, >90% @4 Å

gain at the boundary, should there be slight mechanical mismatch. Also, in the unlikely event that a particular segment has to be powered down, it permits a controlled tailoring of gain reduction at the segment boundary without the need of a larger diameter guard wire.

5. Summary

A brief outline has been given of the design, construction and initial results of an advanced position sensitive neutron detector for protein crystallography. Table 1 shows the key parameters of the detector. The major, new attributes of this device are as follows:

- Eight identical, independent multiwire segments, providing modularity and very high count rate capability—4 μs per segment occupation time.
- Single gas volume and overlapping readout at segment boundaries provides equivalent of single, seamless detector, 150 cm × 20 cm in area, with over 10^5 resolution elements.
- Position errors due to parallax eliminated along the 1.5 m length by the detector's appropriate radius of curvature.
- Position modulation due to anode wires reduced significantly by recently developed electrode structure.
- Front-end encoding electronics optimized for high throughput and low noise—global rate > 10^6 s^{-1}, position resolution <1.5 mm FWHM.
- Decoding based on high performance digital signal processing, optimized for throughput of analog front-end electronics.

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